EVER
ECOLOGIC VEHICLES • RENEWABLE ENERGIES
MONACO 2009

Multipolar double fed induction generator with two phase secondary winding

L.Ribickis, G.Dilevs, E.Jakobsons
Riga Technical University, Faculty of Power and Electrical Engineering
1 Kalku Str., LV-1050, Riga, LATVIA
Tel.: +371 67089333
Fax.: +371 67089039
E-Mail.: leonids.ribickis@rtu.lv, guntis.dilevs@gmail.com, edgars.jakobsons@inbox.lv
URL: www.rtu.lv

N.Levins, V.Pugachevs
Institute of Physical Power Engineering
21 Aizkraukles Str., LV-1006, Riga, LATVIA
Tel.: +371 6558684
Fax.: +371 6550839
E-Mail : magneton@edi.lv
URL: http://www.lza.lv

Abstract: *This paper posses the construction of induction generator, which has the ability to operate at a low rotation speed. This generator can be applied for directly driven turbine without using the gearbox. The generator is multi pole with all of the windings placed on the stator. Rotor is tooth-like and has no windings on it. Primary winding is three phase, secondary winding is two phase.*

Keywords: induction generator, double fed, wind energy, direct drive.

1. Introduction

Due to the development of wind power generators, the applied technologies have drawn out the main directions of developing generator construction with a target to gain the highest possible efficiency. Nowadays the most common designs for wind generators are permanent magnet synchronous generator (PMSG) and double fed induction generator (DFIG). PMSG can operate directly with the turbine with out gear box due to the large number of pole pairs. But DFIG has the ability of increasing the output power within the increase of the wind speed. This paper posses the original solution of how induction generator could be applied as a directly driven double fed generator for wind electric stations. This generator should be designed in a way that all the windings are placed on the stator, rotor is tooth-like without windings [1-4].

2. Special features of the multipolar double fed induction generator with two phase secondary winding

The construction diagram of the double fed induction generator is shown in the Fig. 1. Primary winding (A-X, B-Y, C-Z) is three phase and secondary winding (a-x, b-y) is two phase to keep the electromagnetic symmetry of the system. Both of the windings are placed in the slots of the stator. Rotor is tooth-like and has no windings on it. The number of rotor teeth Z_R is 25 and it corresponds to 25 pole pairs. For creation of the required electromagnetic link between windings it is necessary to have appropriate phase shifts between the processes going in pole extensions. For this purpose the pole extensions are divided into four groups. Each pole extension from the same phase has a phase shift of 90^0 between two groups. Two groups are embraced with the one coil of one secondary phase winding. This feature gives the phase shift for the currents i_a and i_b of 90^0. The pole extensions in the same group are divided with grooves where the primary windings A-X, B-Y and C-Z are placed. The step between the mixed pole extensions belonging to one group equals $t_1 = 2t_Z/3$, and that between the mixed pole extensions belonging to mixed groups equals $t_2=23t_Z/12$. This provides a phase shift of the pole extensions of 240 degrees within the same group, and of 30 degrees for mixed group [10].

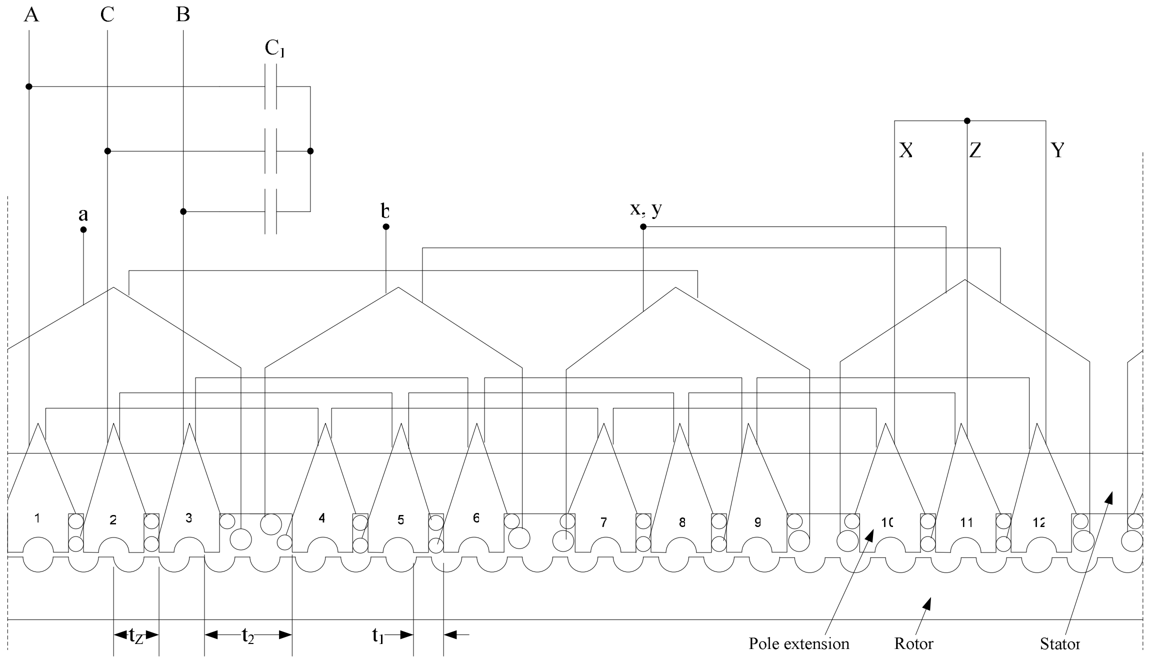

Figure 1: The construction diagram of the multipolar induction generator with two phase secondary winding; t_Z – tooth step of the rotor; t_1 – tooth step between pole extensions; t_2 – tooth step between pole extension groups.

3. The basic equations of the mutlipole induction generator with two phase secondary winding

The equations are similar to those for the conventional induction machine having two phase secondary winding on the rotor. The equations given below describe the electromagnetic processes in the multipolar induction machine. Magnetic flux linkage can be obtained with the matrix equation

$$[\Psi_{ik}] = [w_{ik}] \times [\lambda_{ik}] \times [w_{ik}]^T \times [i_{ik}], \qquad (1)$$

where

$$[\Psi_{ik}] = \begin{bmatrix} \Psi_A \\ \Psi_B \\ \Psi_C \\ \Psi_a \\ \Psi_b \end{bmatrix}$$ is the column matrix of magnetic flux linkages of the windings;

$$[i_{ik}] = \begin{bmatrix} i_A \\ i_B \\ i_C \\ i_a \\ i_b \end{bmatrix}$$ is the column matrix of currents in the windings;

$$[w_{ik}] = \begin{bmatrix} w_k & 0 & 0 & w_k & 0 & 0 & w_k & 0 & 0 & w_k & 0 & 0 \\ 0 & w_k & 0 & 0 & w_k & 0 & 0 & w_k & 0 & 0 & w_k & 0 \\ 0 & 0 & w_k & 0 & 0 & w_k & 0 & 0 & w_k & 0 & 0 & w_k \\ w_k & w_k & w_k & 0 & 0 & 0 & -w_k & -w_k & -w_k & 0 & 0 & 0 \\ 0 & 0 & 0 & w_k & w_k & w_k & 0 & 0 & 0 & -w_k & -w_k & -w_k \end{bmatrix}$$

is the rectangular matrix of the winding turns per each coil according to Fig. 1, where the rows represent the phases and the columns represent the pole extensions. The sign “–” shows the secondary winding direction according to the primary winding direction.

$[\lambda_{ik}]=\begin{bmatrix} \lambda_1 & 0 & ... & 0 \\ 0 & \lambda_2 & ... & 0 \\ ... & ... & ... & 0 \\ 0 & 0 & ... & \lambda_{12} \end{bmatrix}$ is the diagonal matrix of magnetic conductivities, where $\lambda_k = a_0 + a_1 \cos(z_R\alpha - \gamma(k-1))$ is magnetic conductivity of K-th pole extension represented by the Fourier series as a function of the turning angle *α* of the rotor, *a₀* – constant component, *a₁* – component of the first harmonic [5]. The equations, which express magnetic flux linkage for each phase, are

$$\Psi_A = w_{k1}\begin{pmatrix} \lambda_1(w_{k1}i_A + w_{k2}i_a)+ \\ +\lambda_7(w_{k1}i_A - w_{k2}i_a)+ \\ \lambda_4(w_{k1}i_A + w_{k2}i_b)+ \\ +\lambda_{10}(w_{k1}i_A - w_{k2}i_b)+ \end{pmatrix} =$$

$$= 4a_0 w_{k1}^2 i_A + 2a_1 w_{k1} w_{k2} i_a \cos(Z_R\alpha) + ;(2)$$

$$+ 2a_1 w_{k1} w_{k2} i_b \cos(Z_R\alpha - 90^0)$$

$$\Psi_B = w_{k1}\begin{pmatrix} \lambda_3(w_{k1}i_B + w_{k2}i_a)+ \\ +\lambda_9(w_{k1}i_B - w_{k2}i_a)+ \\ \lambda_6(w_{k1}i_A + w_{k2}i_b)+ \\ +\lambda_{12}(w_{k1}i_B - w_{k2}i_b)+ \end{pmatrix} =$$

$$= 4a_0 w_{k1}^2 i_B + 2a_1 w_{k1} w_{k2} i_a \cos(Z_R\alpha - 120^0) + ;$$

$$+ 2a_1 w_{k1} w_{k2} i_b \cos(Z_R\alpha - 210^0)$$

$$\Psi_C = w_{k1}\begin{pmatrix} \lambda_2(w_{k1}i_C + w_{k2}i_a)+ \\ +\lambda_8(w_{k1}i_C - w_{k2}i_a)+ \\ \lambda_5(w_{k1}i_C + w_{k2}i_b)+ \\ +\lambda_{11}(w_{k1}i_C - w_{k2}i_b)+ \end{pmatrix} =$$

$$= 4a_0 w_{k1}^2 i_C + 2a_1 w_{k1} w_{k2} i_a \cos(Z_R\alpha - 240) + ;$$

$$+ 2a_1 w_{k1} w_{k2} i_b \cos(Z_R\alpha - 330^0)$$

$$\Psi_a = w_{k2}\begin{pmatrix} \left(\sum_{k=1}^{6}\lambda_k\right) w_{k2}i_a + (\lambda_1 - \lambda_7)w_{k1}i_A + \\ +(\lambda_3 - \lambda_9)w_{k1}i_B + \\ +(\lambda_2 - \lambda_8)w_{k1}i_C \\ \end{pmatrix} = ;$$

$$= 6a_0 w_{k2}^2 i_a + 2a_1 w_{k1} w_{k2} i_A \cos(Z_R\alpha) +$$

$$+ 2a_1 w_{k1} w_{k2} i_B \cos(Z_R\alpha - 120^0) +$$

$$+ 2a_1 w_{k1} w_{k2} i_C \cos(Z_R\alpha - 240^0)$$

$$\Psi_b = w_{k2}\begin{pmatrix} \left(\sum_{k=1}^{6}\lambda_k\right) w_{k2}i_b + (\lambda_4 - \lambda_{10})w_{k1}i_A + \\ +(\lambda_6 - \lambda_{12})w_{k1}i_B + \\ +(\lambda_5 - \lambda_{11})w_{k1}i_C \\ \end{pmatrix} =$$

$$= 6a_0 w_{k2}^2 i_b + 2a_1 w_{k1} w_{k2} i_A \cos(Z_R\alpha - 90^0) +$$

$$+ 2a_1 w_{k1} w_{k2} i_B \cos(Z_R\alpha - 210^0) +$$

$$+ 2a_1 w_{k1} w_{k2} i_C \cos(Z_R\alpha - 330^0)$$

The equations of voltage for this type of generator are the same as for the conventional induction machine:

$$u_{AB} = i_A R_1 + \frac{d\Psi_A}{dt}$$

$$u_{BC} = i_B R_1 + \frac{d\Psi_B}{dt}$$

$$u_{CA} = i_C R_1 + \frac{d\Psi_C}{dt}$$

$$u_a = i_a R_2 + u_{Ca} + \frac{d\Psi_a}{dt} \qquad (3)$$

$$u_b = i_b R_b + u_{Cb} + \frac{d\Psi_b}{dt} \qquad (2)$$

where

u_{AB}, $u_{BC,}$ u_{CA} are the grid line voltages;
i_A, i_B, i_C are the phase currents of the generator;
i_a, i_b are the currents in secondary circuit;
R_1, R_2 is the active resistance of primary and secondary windings;
u_{Ca},u_{Cb} is the voltage drop on capacitor C_2 of the secondary winding.

With these equations it is possible to solve the most difficult tasks which are met in application of multipolar induction generators – e.g. analysis of transient process.

The project is based on the idea that during the rotation the secondary winding generates the EMF proportional to the slip $s = 1 - \frac{nZ_R}{60 f_1}$

(where f_1 is the frequency of primary current). If the absolute value of the slip increases, the power generated by the secondary winding also increases. The results of practical research have shown that with such a machine a reliable power generation and high efficiency can be achieved [7].

4. The control and operation of the secondary circuit

The secondary winding is switched through the variable capacitors and semiconductor device to the grid. Semiconductor device includes rectifier part, filter, buck-boost converter, filter and inverter.

To increase the value of the current in the secndary circuit and power generated to the grid from the primary circuit, the operating mode of the induction generator has to be close to the resonance mode. This mode can be achieved by controlling the power factor in the secondary circuit according to the slip *s*. In the proposed design the operation of secondary winding is designed in a way that the power could be transferred back to the grid. The circuit diagram is shown if Figure 2.

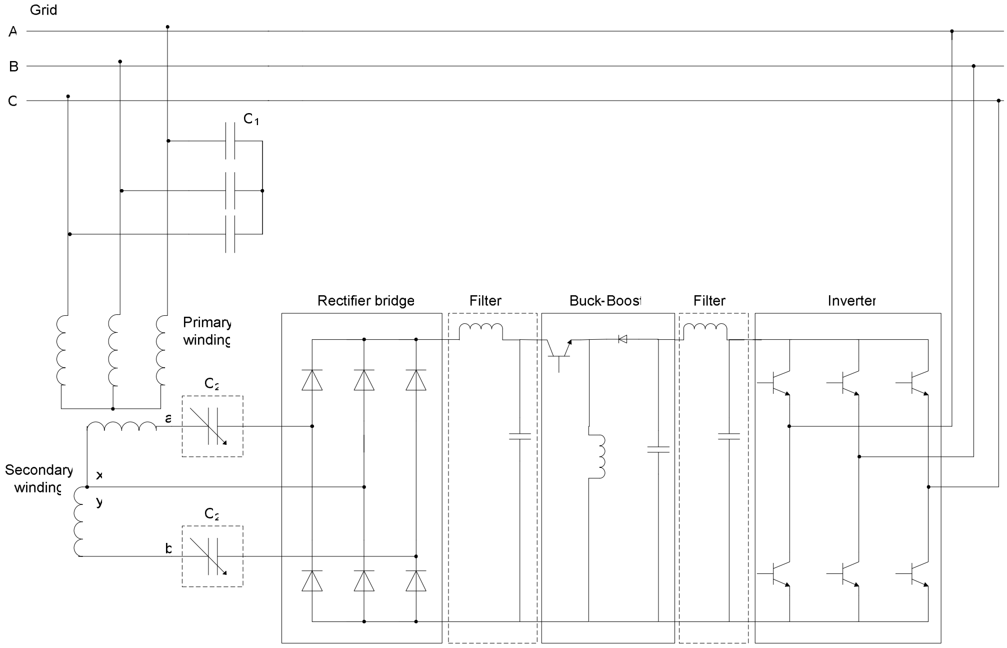

Figure 2: The basic circuit diagram of the multipolar double fed induction generator with two phase secondary winding.

The amplitude of the voltage, generated in the secondary circuit depends on the slip of the generator. This may cause the voltage fluctuations in the rectifier whenever the rotation frequency of the rotor changes. To keep the supply voltage to the inverter stable the buck – boost converter is used. The inverter then supplies constant voltage with constant frequency to the grid [6].

5. The results of the practical research

The practical research was done for the multipolar induction machine with the parameters given in the Table 1.

Table 1: The results of the practical research

No	Measured values and parameters	unit	value
1	2	3	4
1	Stator diameter, D	mm	300
2	Stator length, l	mm	250
3	Number of pole extensions	-	12
4	Number of teeth in one pole extension	-	2
5	Number of teeth in the rotor, Z_R / pole pairs	-	25
6	Number of phases in the primary winding, m_1	-	3
7	Number of phases in the secondary winding, m_2	-	2
8	Primary voltage, U_1	V	380
9	Secondary voltage, U_2	V	57

10	Rotation frequency, n	min^{-1}	244
11	Grid frequency, f_1	Hz	50
12	Power transferred to the grid, P_1	W	1980
13	Power transferred to the secondary circuit, P_2	W	1870
14	Slip, s	-	-1,11
15	Capacitors, C_1/C_2	μF	56/74
16	Power factor, cosφ	-	0,95
17	Efficiency factor, η	-	0,79

6. Conclusions

The advantages of the proposed design are as follows:

1. This machine is designed in a way that it can be applied as a directly driven wind or hydro generator for small power stations. With the multipolar construction power station does not require gear box any more.
2. The generated power for the slip s = – (1…2) can be transferred through the primary and secondary windings. There are extended limits for raising the output power if the rotation speed of the generator is increasing.
3. The two phase secondary winding provides electromagnetic symmetry, which significantly reduces the presence of THD in the primary winding.
4. The fully controlled secondary circuit allow the limits of the generator's installed power to be extended.

References

[1] Ackerman T., Wind Power in Power Systems. Royal Institute of Technology Stockholm, Sweden, John wiley & Sons, Ltd. 2005, 694 pages.

[2] Daskova J., Kamolins E., Levins N. Multipolar directly driven wind generators. Latvian journal of Physics and Technical sciences, Nr.4, 2004.gads. pages 41 – 47. *(in Latvian)*

[3] The new generation of wind energy converters. Pitch Wind Systems AB, Sweden, 2001.

[4] Enercon grid properties and wind farm managemant, Enercon, Hamburg, 2002. 15 pages.

[5] Pugachev V., Levin N., Ribickis L., Manonov M., A multipolar inductor generator of annular design for windmills. Riga RTU Power and electrical engineerings 4, 10. 2003.gads, 10 – 15 pages.

[6] Nordex N54/1000 kW MK3, Technical Overview Svindblek 7323 Give Denmark, 1996, 4 pages.

[7] Voldek A., Electrical machines. Energia 1974, 640 pages. *(in Russian)*

[8] Kopilov I., Klokov B., Morozkin V., Tokarev B. Design of electrical machines, Moskva, VSh. 2005. 768 pages. *(in Russian)*

[9] Postnikov I. Design of electrical machines, GITL USSR, Kiev 1952. 736 pages. *(in Russian)*

[10] Levin N., Serebriakov A., Electrical machines and drives, 3.ed, Electrical drives based on the motors with static windings, Riga 1976, 192 pages.

[11] Dilevs G., Levins N., Pugachevs V., Ribickis L. Double fed induction generator. Patents application P – 03 – 101, 20.09.2007, 8 pages.